

Performance analysis of a model predictive unified power flow controller (MPUPFC) as a solution of power system stability

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Abstract— This paper addresses model predictive controller (MPC) as a powerful solution for improving the stability of an FACTS device like unified power flow controller (UPFC) connected single machine infinite bus (SMIB) power system. UPFC is mainly used in the transmission systems which can control the power flow by controlling the voltage magnitude, phase angle and impedance. And as a controller, MPC, not only provides the optimal control inputs, but also predicts the system model outputs which enable it to reach the desired goal. So, model predictive unified power flow controller (MPUPFC), a combination of UPFC and MPC along with proper system model parameters can provide a satisfactory performance in damping out the system oscillations making the system stable. Simulation is done in Matlab. Response is shown for 4 different states. Effects are shown for 4 control signals of UPFC operating individually and combining 2 at a time.

Keywords— Power system stability, system model, UPFC, FACTS, MPC.

I. INTRODUCTION

Power system oscillations are an inevitable phenomenon of the system. Faults and weak protective relaying operation can cause the oscillation to collapse the system [1]. In order to damp these power system oscillations, different devices and control methods are used [2]. FACTS technology is the newest way of improving power system operation controllability and power transfer limits which has been added in the stream with the progress in the field of power electronics devices. FACTS devices can cause a substantial increase in power transfer limits during steady state operation [3]. Among the FACTS devices, UPFC is the one having very

attractive and effective features. It is capable of providing simultaneous control of voltage magnitude and active and reactive power flows, in adaptive fashion. It has the ability to control the power flow in transmission line, improve the transient stability, mitigate system oscillation and provide voltage support [1, 4].

A number of researches had been done to find out the control schemes for performing the oscillation-damping task of UPFC. Among the controllers which are used to control the FACTS devices, model predictive controller (MPC) has got a wide range of attractive and versatile features. Now a day, this controller is widely used in the field of industry as it has the ability to implement constraints in control process system. A good overview of industrial linear MPC techniques can be found in [5-7].

In this paper, model predictive Controller (MPC) has been chosen to control UPFC. Attractive features of these two tools jointly provide a very satisfactory solution to the system stability. System model of SMIB system along with UPFC is controlled here with MPC for four different control signals of UPFC. Impact of the system for different combinations of control signals is also investigated.

II. SYSTEM DYNAMIC MODEL

The power system [8] that is studied in this paper consists of a synchronous generator connected to transmission lines and an infinite bus via two transformers. The UPFC consists of an excitation transformer (ET), a boosting transformer (BT), two three-phase GTO based voltage source converters (VSCs); which are connected to each other with a common dc link capacitor [1].

Fig. 1 shows a SMIB system equipped with an UPFC. The four input control signals to the UPFC

are m_E , m_B , δ_E , and δ_B . Where, m_E is the excitation amplitude modulation ratio, m_B is the boosting amplitude modulation ratio, δ_E is the excitation phase angle, and δ_B is the boosting phase angle.

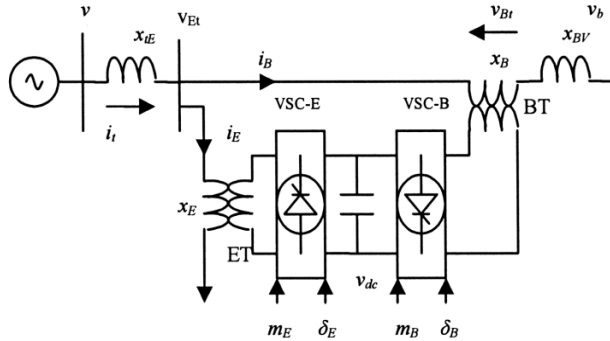


Fig 1: SMIB power system equipped with UPFC

In stability and control studies of power system oscillations, the linearized model can be used. In this paper dynamic model of the system for small signal stability improvement is used. Nominal parameters used for system modeling are given in Appendix-I.

The nonlinear model of the SMIB system of Fig 1 can be expressed by the following differential equations (1-4) [8]:

$$\dot{\delta} = \omega_{base}(\omega - 1) \dots \dots \dots (1)$$

$$\dot{\omega} = \frac{1}{2H} [P_m - P_e - D(\omega - 1)] \dots \dots \dots (2)$$

$$\dot{E}_q' = \frac{1}{T_{d0}} [E_{fd} - E_q' - (x_d - x_d')i_d] \dots \dots \dots (3)$$

$$\Delta \dot{E}_{fd} = K_A((V_{ref} - v + U_{pss}) - E_{fd}) \frac{1}{T_A} \dots (4)$$

where P_m and P_e are the input and output power, respectively. $P_e = v_d i_d + v_q i_q$, $v_t = \sqrt{(v_d^2 + v_q^2)}$,

$$v_d = x_q i_q = x_q (i_{iq} + i_{lq}), v_q = E_q' - x_d' i_d,$$

$$i_d = i_{Ed} + i_{Bd}, i_q = i_{Eq} + i_{Bq},$$

M and D the inertia constant and damping coefficient, respectively; ω_{base} the synchronous speed; δ and ω the rotor angle and speed, respectively; E_q' , E_{fd} , and v the generator internal, field and terminal voltages, respectively; T_{d0} the open circuit field time constant; x_d and x_d' the d-axis reactance, d-axis transient reactance respectively; K_A and T_A the exciter gain and time constant, respectively; V_{ref} the reference voltage; and u_{pss} the PSS control signal.

By applying Park's transformation and neglecting the resistance and transients of the ET and BT transformers, the UPFC can be modeled by the following equations (5-7):

$$\begin{bmatrix} v_{Edt} \\ v_{Etq} \end{bmatrix} = \begin{bmatrix} 0 & -x_E \\ x_E & 0 \end{bmatrix} \begin{bmatrix} i_{Ed} \\ i_{Eq} \end{bmatrix} + \begin{bmatrix} \frac{m_E \cos \delta_E v_{dc}}{2} \\ \frac{m_E \sin \delta_E v_{dc}}{2} \end{bmatrix}$$

..... (5)

$$\begin{bmatrix} v_{Bdt} \\ v_{Btq} \end{bmatrix} = \begin{bmatrix} 0 & -x_B \\ x_B & 0 \end{bmatrix} \begin{bmatrix} i_{Bd} \\ i_{Bq} \end{bmatrix} + \begin{bmatrix} \frac{m_B \cos \delta_B v_{dc}}{2} \\ \frac{m_B \sin \delta_B v_{dc}}{2} \end{bmatrix}$$

..... (6)

$$\dot{v}_{dc} = \frac{3m_E}{4C_{dc}} (\cos \delta_E i_{Ed} + \sin \delta_E i_{Eq}) + \frac{3m_B}{4C_{dc}} (\cos \delta_B i_{Bd} + \sin \delta_B i_{Bq})$$

..... (7)

Where, v_{Et} , i_E , v_{Bt} , and i_B are the excitation voltage, excitation current, boosting voltage, and boosting current, respectively; C_{dc} and v_{dc} are the DC link capacitance and voltage.

By combining and linearizing the equations (1-7) state space equations of system will be obtained which are present in equations (8). In this process there are 28 constants denoted by k are being used.

$$\dot{\Delta X} = A \Delta X + B \Delta U \dots \dots \dots (8)$$

where the state vector ΔX and control vector ΔU are $\Delta X = [\Delta \delta \quad \Delta \omega \quad \Delta E_q' \quad \Delta E_{fd} \quad \Delta V_{dc}]^T$
 $\Delta U = [\Delta U_{pss} \quad \Delta m_E \quad \Delta \delta_E \quad \Delta m_B \quad \Delta \delta_B]^T$

Where

$$A = \begin{bmatrix} 0 & \omega_b & 0 & 0 & 0 \\ -\frac{K_1}{M} & -\frac{D}{M} & -\frac{K_2}{M} & 0 & -\frac{K_{pd}}{M} \\ \frac{K_4}{T_{d0}} & 0 & \frac{K_3}{T_{d0}} & \frac{1}{T_{d0}} & \frac{K_{qd}}{T_{d0}} \\ -\frac{K_A K_5}{T_A} & 0 & -\frac{K_A K_6}{T_A} & -\frac{1}{T_A} & -\frac{K_A K_{vd}}{T_A} \\ K_7 & 0 & K_8 & 0 & -K_9 \end{bmatrix}$$

and

$$B = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & -\frac{K_{pe}}{M} & -\frac{K_{pde}}{M} & -\frac{K_{pb}}{M} & -\frac{K_{pdb}}{M} \\ 0 & -\frac{K_{qe}}{T'_{d0}} & -\frac{K_{qde}}{T'_{d0}} & -\frac{K_{qb}}{T'_{d0}} & -\frac{K_{qdb}}{T'_{d0}} \\ \frac{K_A}{T_A} & \frac{K_A K_{ve}}{T_A} & \frac{K_A K_{vde}}{T_A} & \frac{K_A K_{vb}}{T_A} & \frac{K_A K_{vdb}}{T_A} \\ 0 & K_{ce} & K_{cde} & K_{cb} & K_{cdb} \end{bmatrix}$$

III. DAMPING CONTROL

The unique feature of MPC which has made it different from other controllers is the ability to predict the future response of the plant. At each control interval an MPC algorithm attempts to optimize future plant behavior by computing a sequence of future manipulated variable adjustments [9]. Figure 2 shows the basic working principle of MPC.

Prediction horizon (TP) is the time range which, future system outputs are predicted in it. Control horizon (Tc) is the time steps number that input control sequence calculations for the prediction horizon are done [9]. In this plant model, value of prediction horizon is taken 20 and control horizon is 2.

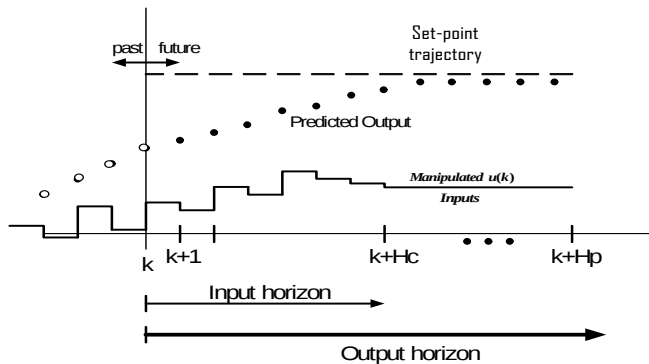


Fig 2: The receding horizon principle of model predictive control

At a current instant k , the MPC solves an optimization problem over a finite prediction horizon $[k, k + H_p]$ with respect to a predetermined objective function such that the predicted state variable $\hat{x}$ or output $\hat{y}$ can optimally stay close to a reference trajectory. The control is computed over a control horizon $[k, k + H_c]$, which is smaller than the prediction horizon ($H_c \leq H_p$). If there were no disturbances, no model-plant mismatch and the

prediction horizon is infinite, one could apply the control strategy found at current time k for all times. However, due to the disturbances, model-plant mismatch and finite prediction horizon, the true system behavior is different from the predicted behavior. In order to incorporate the feedback information about the true system state, the computed optimal control is implemented only until the next measurement instant $(k, k + 1)$, at which point the entire computation is repeated [10].

MPC approach can be expressed considering the following finite horizon cost function [10]

$$J^h(x_t, [u_0(t), \dots, u_{H-1}(t)]) = \sum_{i=1}^{H-1} h(\bar{x}_{t+i\Delta T}(u), u_i(t)) + g(\bar{x}_{t+H\Delta T}(u))$$

where t is the current time; H is the length of the optimization horizon; ΔT is the sample period. If $i > 0$, then $\bar{x}_{t+i\Delta T}(u)$ denotes the controlled trajectory at time $t + i\Delta T$ from x_t under piecewise controls $u = [u_0(t), \dots, u_{i-1}(t)] \in U^H$; h is the running cost; and g is the terminal cost. We assume that h is non-negative function and g satisfies $g(x) \geq \alpha |x - x_{eq}|$ for all x , where x_{eq} is some desired equilibrium and $\alpha > 0$ is some positive constant. That is, g is an 'upward' function whose lowest point is at the system equilibrium. This condition on $g(\cdot)$ ensures that the control design attempts to reach the system equilibrium.

Fig 3 shows a complete block representation of UPFC connected SMIB system controlled with MPC.

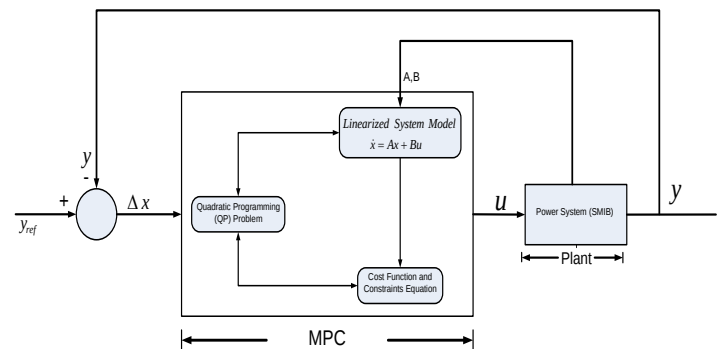


Fig 3: Block diagram representation of UPFC connected SMIB system controlled with MPC

The UPFC connected SMIB power system plant is connected here with the MPC block. The output of the plant (y) enters into the summing junction where it has been compared with the reference value (y_{ref}). Subtracted result (Δy) goes into the MPC block. The

information about the plant (system matrix A,B) are already given to the MPC block. So, the linearized system model of the plant gives the future output (u) with the help of Quadratic Programming (QP) function of MPC and proper constraints of the MPC block. Predicted output of the controller, u enters into the plant and creates the next result y' . Thus the loop will continue until it reaches the desired reference trajectory of the plant.

Figure 4 show the circuitual representation of UPFC connected SMIB system controlled with MPC which is actually the modification of Fig 1.

Four control signals of UPFC (m_E , m_B , δ_E , and δ_B) are entering into the UPFC connected SMIB plant through MPC. Thus MPC is connected with the system model through UPFC.

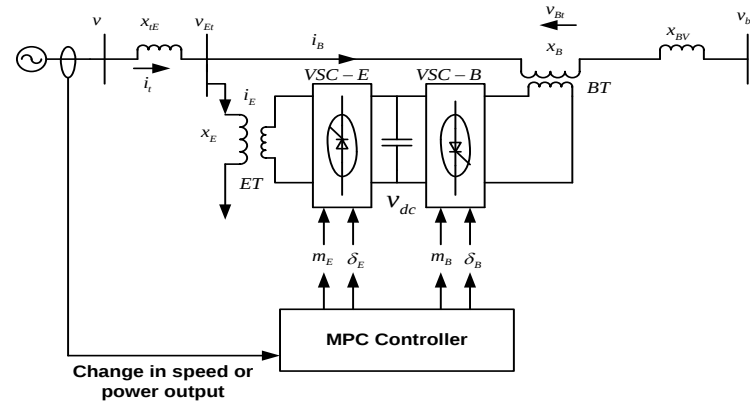


Fig 4: Circuitual representation of UPFC connected SMIB system controlled with MPC (modification of Fig 1)

IV. SIMULATION RESULTS

A disturbance of pulse type signal is given in the system's ΔP_e . Disturbance duration (period) is 0.1 sec, disturbance amplitude (size) is 1 unit and disturbance occurring time is 1 sec.

Value of prediction horizon is taken as 10, control horizon is 2 and control interval is chosen as 0.5 in Matlab MPC toolbox.

Response of MPC on proposed model is observed for 4 different states $\Delta\delta$, $\Delta\omega$, $\Delta E'_q$ and ΔE_{fd} . Individual effects of 4 different control signals m_E , δ_E , m_B and δ_B on system states are observed first in figure (5-8)

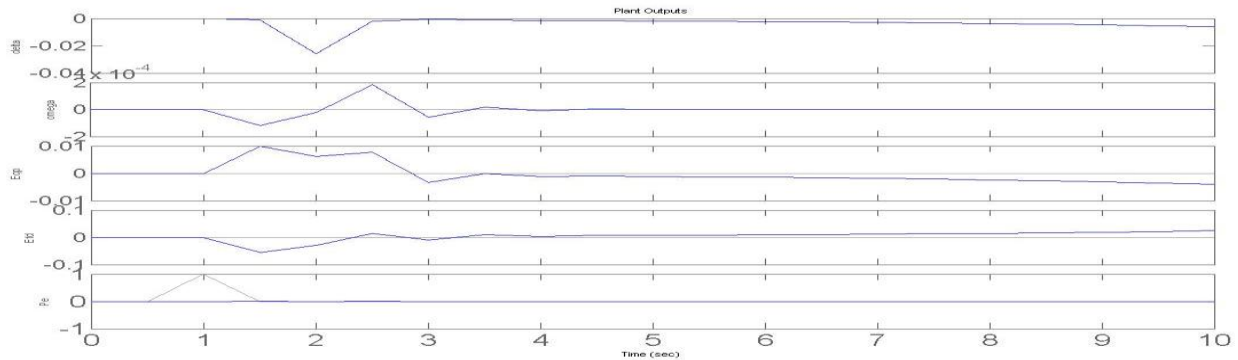


Fig 5: Responses for control signal m_E for states (i) $\Delta\delta$, (ii) $\Delta\omega$, (iii) $\Delta E'_q$ and (iv) ΔE_{fd}

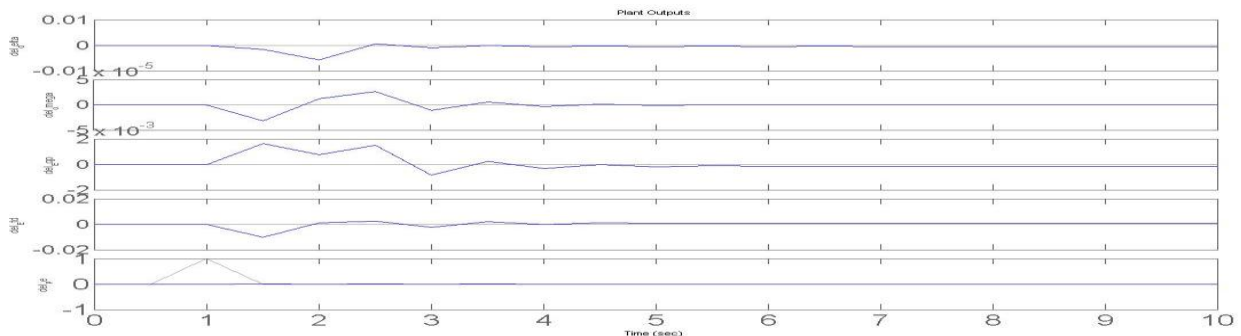


Fig 6: Responses for control signal m_B for states (i) $\Delta\delta$, (ii) $\Delta\omega$, (iii) $\Delta E'_q$ and (iv) ΔE_{fd}

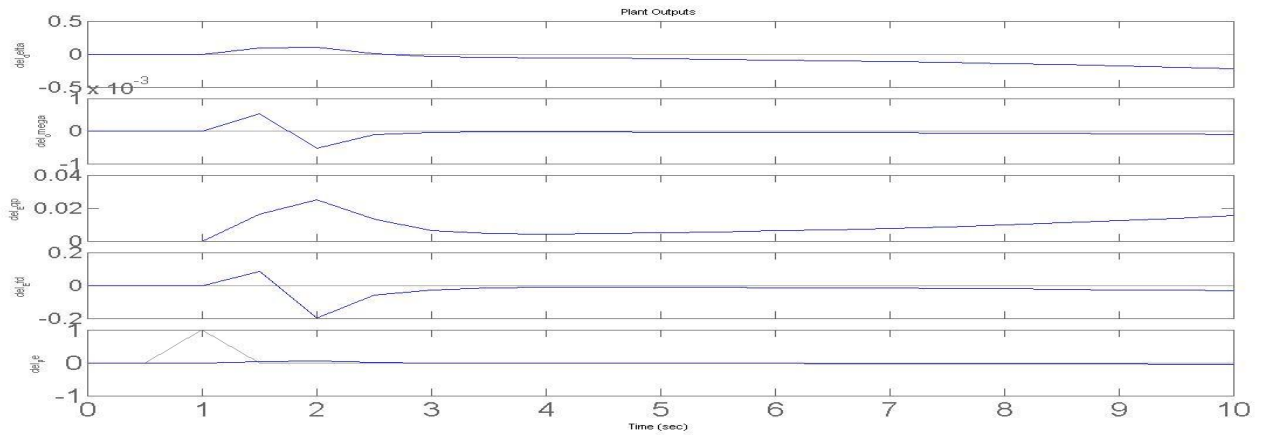


Fig 7: Responses for control signal δ_E for states (i) $\Delta\delta$, (ii) $\Delta\omega$, (iii) $\Delta E'_q$ and (iv) $\Delta E'_d$

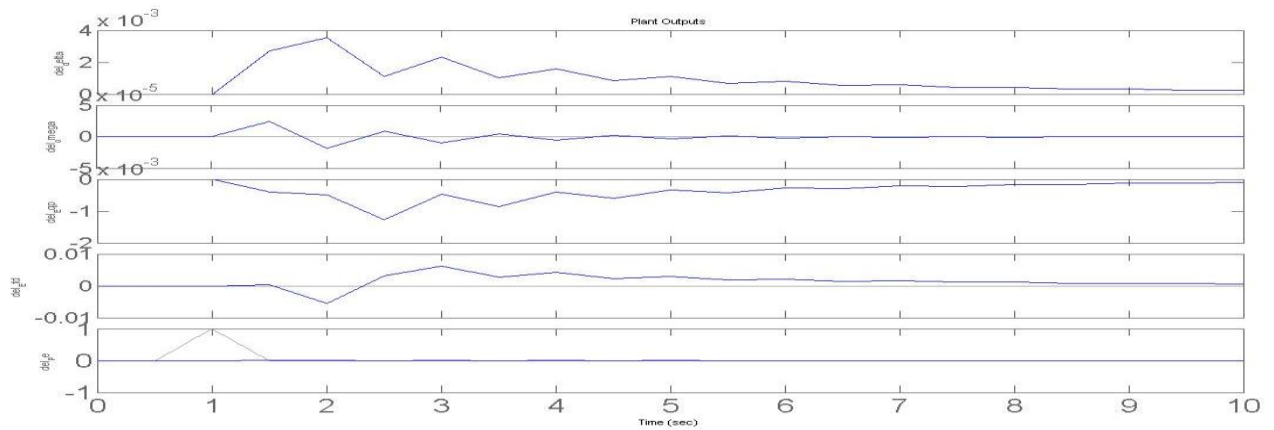


Fig 8: Responses for control signal δ_B for states (i) $\Delta\delta$, (ii) $\Delta\omega$, (iii) $\Delta E'_q$ and (iv) $\Delta E'_d$

It has been seen that m_E (Fig. 5) and δ_E (Fig. 7) give the worse response. They can bring stability only in state $\Delta\omega$. Control signal δ_B also doesn't have a good response characteristics (Fig. 8). It can stable several states but takes a long time for that. Among the four signals, m_B gives the best output making all the 4 states stable at a reasonable time of below 6 seconds (Fig. 6).

An exceptional and effective feature of MPC is the ability to provide support to the MIMO plants. Most MPC toolbox

applications involve plants having multiple inputs and outputs. Here, combination of different control signals of UPFC is now applied as input to the plant to observe the responses on different states.

Then, the responses are observed for different combinations of control signals two at a time. Four different combinations of two control signals are observed in this paper in fig (9-12).

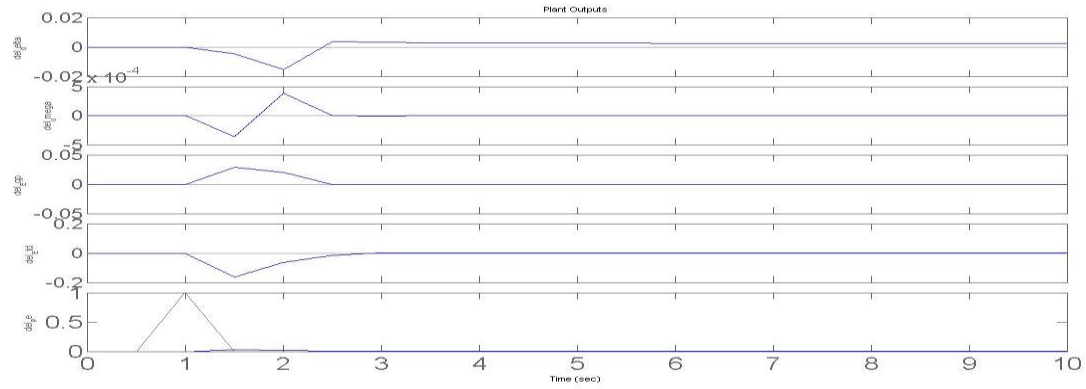


Fig 9: Responses for control signal m_B and m_E together for states (i) $\Delta\delta$, (ii) $\Delta\omega$, (iii) $\Delta E'_q$ and (iv) ΔE_{fd}

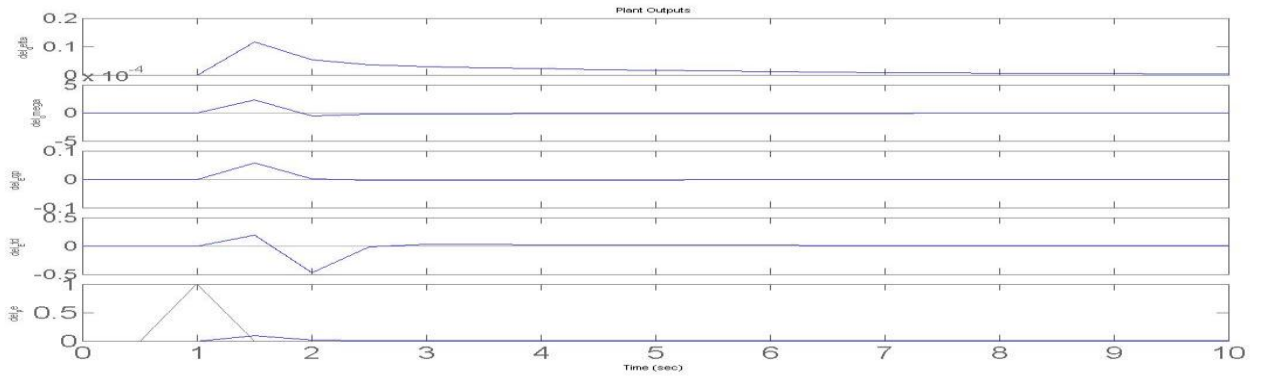


Fig 10: Responses for control signal δ_B and δ_E together for states (i) $\Delta\delta$, (ii) $\Delta\omega$, (iii) $\Delta E'_q$ and (iv) ΔE_{fd}

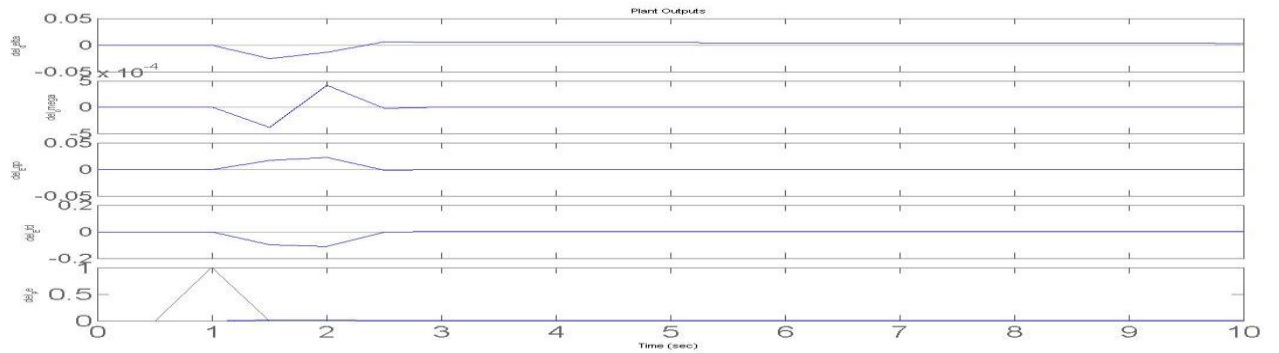


Fig 11: Responses for control signal m_B and δ_B together for states (i) $\Delta\delta$, (ii) $\Delta\omega$, (iii) $\Delta E'_q$ and (iv) ΔE_{fd}

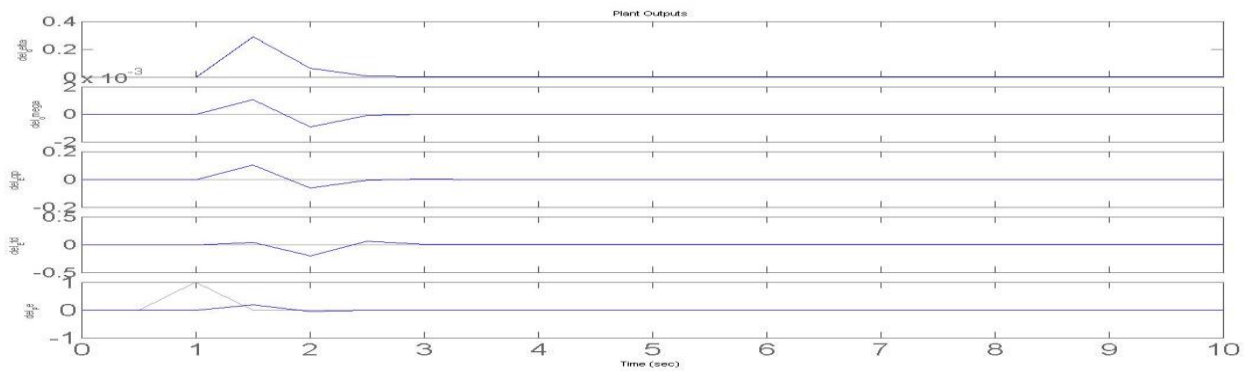


Fig 12: Responses for control signal m_B and δ_E together for states (i) $\Delta\delta$, (ii) $\Delta\omega$, (iii) $\Delta E'_q$ and (iv) ΔE_{fd}

Observing the combined effect of two different control signals, it has been found that the responses are significantly improved for every case than applying them individually. Among the 5 combinations, combination of δ_E and δ_B takes a long

time to settle $\Delta\delta$ (Fig. 10). But the other 4 states are settled down within 3 seconds. Combination of m_B - δ_B (Fig. 11), m_E - m_B (Fig. 9) and m_B - δ_E (Fig. 12) show the best responses here making all the 5 states stable within a short time of 3 seconds.

CONCLUSION

In this paper by linearizing and combining the equations of single machine infinite bus power system and unified power flow controller, a complete state space model of SMIB power system including UPFC was presented. Effect for model predictive controller for stability analysis is observed then for different states of the system model. Different combinations and individual impacts of four different control signals of UPFC are analyzed. It has been found that the system performs better if MPC is allowed to operate with multiple control signals of UPFC. Impact of MPC as MIMO plant is thus evident. Best solution of stability analysis for the

proposed model is the use of MPC with four control signals of UPFC at a time.

Appendix:

The parameters used in system model:

Generator: $M = 8$ MJ/MVA, $T'_{d0} = 5.044$ s, $D = 0$, $X_q = 0.6$ pu, $X_d = 1.0$ pu, $X'_d = 0.3$ pu

Transformers: $X_T = 0.1$ pu, $X_E = 0.1$ pu, $X_B = 0.1$ pu

Transmission line : $XL = 0.1$ pu

Operating condition: $P_e = 0.8$ pu, $Q = 1.670$ pu, $V_b = 1$ pu, $V_t = 1$ pu

DC link parameter: $V_{DC} = 2$ pu, $C_{DC} = 1.2$ pu

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